Low Gravity on Ocean Worlds Can Help to Sustain Low-to-Moderate Temperature Hydrothermal Circulation

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Introduction and Goals: Several ocean worlds may sustain active, seafloor hydrothermal systems, but the characteristics and controls on fluid-heat transport in these systems are not well understood. We developed three-dimensional numerical simulations, using a ridge-flank hydrothermal system on Earth as a reference, to test the influence of ocean-world gravity on fluid and heat transport. Simulations had ranges of heat input at the base; aquifer thicknesses, geometry, and permeability; and gravity values appropriate for Earth, Europa, and Enceladus. We tested when a "hydrothermal siphon" could be sustained; quantified circulation temperatures, flow rates, and advective heat output; and evaluated implications for similar processes occurring on ocean worlds (*Fisher et al.*, 2024 - *in review*). We have also begun to quantify the effect these changes might have on fluid chemistry and thus habitability.

Simulation Configuration: The hydrothermal system on Earth that is used as a reference and starting point for this study is located on ~3.5 M.y. old seafloor of the Juan de Fuca Plate. An outcrop-to-outcrop circulation system within the upper ~1 km subseafloor operates in this region where permeable, volcanic ocean crust is mostly covered by thick, low-permeability sediment. Thick sediment in this area largely limits advective hydrothermal exchange with the overlying ocean, and seafloor heat flux is close to that predicted by conductive lithospheric cooling models, ~200 mW/m^2. At the field site, water recharges through a large outcrop and flows laterally ~50 km, where it discharges through a smaller outcrop at ~10 kg/s. This hydrothermal siphon is driven by pressure difference at the base of cooler (denser) and warmer (less dense) water columns in the crust. Hydrothermal (water-rock) reaction temperatures are ~65 °C, and earlier simulations of this area are consistent with fluid flow mainly in the upper volcanic crust, and aquifer permeability of $\boldsymbol{k}_{aq} = 3 \times 10^{-13}$ m^2 to 2×10^{-12} m^2 (*Winslow et al.*, 2016).

The Influence of Ocean World Gravity:

Parameters tested. New simulations explored the influence of ocean world gravity appropriate for Europa ($\boldsymbol{g}_{Eu}$ = 1.3 m/s^2) and Enceladus ($\boldsymbol{g}_{En}$ = 0.114 m/s^2) hydrothermal circulation conditions and dynamics, with comparison to similar simulations using Earth gravity ($\boldsymbol{g}_{Ea}$ = 9.81 m/s^2). A suite of 49 simulations were run to dynamic steady state with these properties/conditions:

• Rocky aquifer thickness was $\boldsymbol{b}_{aq}$ = 600-1,200 m.

• Heat input at the base of the domain was ~50 to 200 mW/m^2 (25%, 50% and 100% of Earth system).

• Rock (aquifer) permeability was $\boldsymbol{k}_{aq} = 10^{-13}$ m^2 to 10^{-10} m^2, whereas rocky outcrops had permeability of $\boldsymbol{k}_{oc} = 10^{-12}$ to 10^{-10} m^2, with vertical anisotropy =100x.

Primary circulation metrics for the hydrothermal siphons were: discharge temperature ($\boldsymbol{T}_{siph}$), flow rate ($\boldsymbol{F}_{siph}$), and advective heat output ($\boldsymbol{Q}_{siph}$). Secondary metrics included mass water/rock ratios, efficiency of heat extraction, and number of siphons that could be sustained based on geometry and heat budget.

Key results. Hydrothermal siphons were sustained for all gravity values tested, across a range of physical properties, resulting in $\boldsymbol{T}_{siph}$ = 11 to 149 °C, $\boldsymbol{F}_{siph}$ 0.7 kg/s to 2,110 kg/s, and $\boldsymbol{Q}_{siph}$ = 0.2 MW to 710 MW. The highest discharge temperatures were found for the lowest gravity tested ($\boldsymbol{g}_{En}$ =0.114 m/s^2). Hydrothermal siphons were sustained even for moderate and low heat input of ~100 to 50 mW/m^2.

Convection in the rocky aquifer was unstable and mixed, with local rolls superimposed on net lateral flow, and a fraction of recharging fluid flowing to the discharging outcrop. Hydrothermal siphons failed when the pressure difference between recharging and discharging ends was offset by pressure losses resulting from local convection and/or lateral flow between outcrops sites. Aquifer permeabilities that allowed a siphon to be sustained were $\boldsymbol{k}_{aq} = 10^{-13}$ to 10^{-10} m^2, but siphons failed more commonly with lower k_{aq} and/or g values. For higher $\boldsymbol{k}_{aq}$ values, lower $\boldsymbol{g}$ values tended to suppress local convection, allowing outcrop-to-outcrop circulation to be sustained at elevated temperatures and low flow rates; this should lead to greater changes in fluid chemistry due to water/rock reactions.

The time required for systems like those simulated to cycle an entire ocean in and out of the seafloor was short for $\boldsymbol{g}_{Ea}$, ~1 My, whereas ocean circulation times were 10^2 to 10^4 My for $\boldsymbol{g}_{Eu}$ and $\boldsymbol{g}_{En}$. This could help to sustain hydrothermal flows for a long time under ocean world gravity, despite small heat sources to drive circulation. Preliminary calculations of mass water/rock ratios suggest 10^2x to 10^3x differences in median concentrations of major anabolites (C, Ca, Fe, S, P), assuming chemical equilibrium and chondritic and basaltic rock types. Simulations show dramatic variations in the behavior and habitability of simulated hydrothermal system with ocean -world gravity.

Reference:

Fisher, A. T., et al., (2024), *J. Geophys. Res. - Planets*, *in review*

Winslow, D. M. et. al. (2016), *J. Geophys. Res.*, *121*(3), 1365–1382, 10.1002/2015JB01260